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A Study of an Outburst in the Classical Symbiotic Star Z And in a Colliding-Wind Model

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Abstract

Two-dimensional gas-dynamical modeling of the mass-flow structure is used to study the outburst development in the classical symbiotic star Z And. The stage-by-stage rise of the light during the outburst can be explained in the framework of the colliding winds model. We suggest a scenario for the development of the outburst and study the possible influence of the changes of the flow structure on the light of the system. The model variations of the luminosity due to the formation of a system of shocks are in good agreement with the observed light variations.

1 INTRODUCTION

Mass transfer in symbiotic stars is realized because of the existence of a stellar wind of their cool giant component. Based on radio data Seaquist and Taylor [1] suggest that the radio emission is determined by the wind of the giant, partially ionized by the hot component. The mass-loss rate for

Z And obtained from radio data at 1.465 and 4.885 GHz in July 1982 by Seaquist and Taylor [2] amounts to $\sim 2 \times 10^{-7} M_{\odot}$/yr and the velocity of the wind was estimated to be 25 km/s [3].

The existence of the wind of the hot component of the symbiotic binaries during their active stages is confirmed by the observations at least of some of them, for example the system AG Peg [4]. In 1989 Nussbaumer and Vogel [5] suggested that the white dwarf in Z And can also have a wind. The possibility for the existence of a wind of the hot component of Z And during outburst phase was studied by Nussbaumer and Walder [6].

The observational data obtained during the 2000 – 2002 outburst of Z And indicate the presence of the white dwarf's wind in this system. It is revealed for instance by observations of UV [7, 8] and optical [9] lines. In November and December 2000 the PV λ1117 Å UV line had a variable P Cygni profile with one or two absorption components indicating outflow at velocities of 0 – 300 km/s. In all the cases, however, the maximal depth of the absorption was at velocities of 0 – 50 km/s [7]. Both the optical and the UV data show an increase of the emission component relative to the absorption one during the outburst. The presence of a high velocity flow from the hot component during the light maximum was noted also by Skopal et al. [10]. The analysis of the radio emission confirms the existence of the white dwarf's wind during the outburst of Z And in 2000 [8].

All of these data suggest that both the cool and the hot components have winds in the active phases of classical symbiotic stars and their behavior must be considered in the framework of the colliding winds model.

The first attempts to describe qualitatively the behavior of symbiotic stars supposing existence of a hot component's wind during the outburst were made in 1984 [11–15]. These studies were aimed to explain the observed line profiles. Two-dimensional gas-dynamical modeling of colliding winds was first undertaken in 1993–1996 by Nussbaumer and Walder [6] and Bisikalo et al. [16, 17].

In the present paper we study the structure of the mass flow in the framework of the two-dimensional gas-dynamical model when the winds of the hot and the cool components present. A detailed description of this model can be found in [18], where only the donor's wind is considered. This model was modified - in particular, in the computations where the hot component's wind was taken into account, we used a spatially nonuniform 679×589 grid that becomes denser in the vicinity of the accretor. The use of a denser grid in the vicinity of the accretor and parallel computers enabled us to consider the features of the flow near the accretor in detail. The wind of the accretor was modeled introducing a jump of the parameters at its surface. The boundary conditions were chosen in accordance with the observational data. We considered different cases varying the parameters of the model (pressure, density, and velocity of the outflowing matter). The boundary conditions (more precisely, their variations) were selected to be consistent with the energy of the outburst. A steady-state solution prior to the outburst was chosen as an initial condition, the next computations were realized using modified boundary conditions at the accretor's surface. We based our modeling on the assumption that the wind of the hot component appears after the onset of the outburst. We considered the evolution of the conditions over a time span typical for the outburst development, of the order of hundreds of days. The time required to achieve a steady state was not considered in detail in the framework of our problem.

The results of the computations were used to explain the stage-by-stage nature of the rise of the light during the development of the outburst. A possible scenario for this development is suggested.

2 THE PECULIAR CHARACTER OF THE RISE OF THE Z And LIGHT DURING THE OUTBURST

Z Andromedae is one of the most intensively observed symbiotic stars. Several periods of activity have been detected over more than a hundred years of observations – after 1915, 1939, 1960, 1984, and 2000. On average, the light of the system increases by $2^m - 3^m$ over a period of about 100 days during an outburst, after which it begins to decline and returns to its initial value after several hundred of days.

Detailed light curves were obtained during the last outburst, which clearly show that the rise to the maximal light occurs in a stage-by-stage mode. The light curves obtained during the previous outbursts were not detailed enough to detect this effect. Moreover, only for the two last active phases observational data in different wavelength regions are available (obtained by instruments on spacecraft). *Fig.1*

The UBV light curves for the 2000 outburst are shown in Fig.1. The first stage of the rise of the light started in the end of August 2000 and continued for about 60 days. During that time the light increased by 1.9^m. Further it remained constant one and even slightly decreased over about 25–30 days. The light began to rise again after November 13, 2000, and reached a second maximum (in fact, the overall maximum of the outburst) after approximately 25 days (near December 6, 2000). The times of the first and second maxima are marked in Fig. 1 with dashed lines. *Fig.2*

The most detailed light curve, published by Sokoloski et al. [8] is shown in Fig.2. According to these data, there is one feature more on the curve – a kink that appears about 2.5 weeks after the onset of the outburst. This led Sokoloski et al. [8] to distinguish three stages of the rise of the light, separated by two plateaus. The rise stages last 2.5, 2.5 – 3, and slightly more than 3 weeks respectively, while the first and the second plateaus last one week and about one month.

The existence of the first maximum is explained in the works [8, 21] as being due to clearing of the ejected shell and the future rise of the light is related to the revealing the white dwarf. However, the UV and the optical spectral data presented in [7] and [9] contain P Cygni lines indicating mass outflow from the dwarf at the time of the light maximum. Thus, these observational data cast some doubt on the suggestion made in [8,21].

In the framework of our investigation we have made some attempt to explain the behavior of the light of Z And using the colliding-winds model.

3 DEVELOPMENT OF THE OUTBURST AFTER A WIND OF THE HOT COMPONENT APPEARS

Thermonuclear burning at the surface of the accretor is considered to be the most probable origin for the observed features of symbiotic stars [22, 23]. The burning of hydrogen at the white-dwarf surface depends substantially on the accretion rate [24]. For a narrow range of accretion rates stable hydrogen burning is possible [25–27]. For the mass of the white dwarf in Z And $M = 0.6M_\odot$ this range is $2.1 \cdot 10^{-8} M_\odot / \lesssim \dot{M}^{accr} \lesssim 4.7 \cdot 10^{-8} M_\odot /$.

In the commonly accepted picture the outbursts of classical symbiotic stars realize when the accretion rate exceeds the upper limit for stable hydrogen burning. If this occurs, the accreted matter accumulates in a hydrogen-burning shell and expands to giant dimensions. However, the scale of the observed outbursts casts doubt on the possibility that they are associated purely with accretion processes. The estimates show that the energetics of the 2000 event require an accretion rate exceeding $10^{-5} M_{\odot}/\mathrm{yr}$ [8], in contradiction with both observations and computational results [28]. We considered a "combined" mechanism of the outburst where the increase of the accretion rate due to disruption of the disk results in variations of the burning rate [18, 29–31]. In this case the amount of the accreted matter ($10^{-8} - 10^{-7} M_{\odot}/\mathrm{yr}$ [28]) is sufficient to explain the observed luminosity variations (according to the estimates given in [8], it is necessary to accrete $\sim 10^{-7} M_{\odot}$). A similar model was suggested by Sokoloski et al. [8], who supposed that the disk instability leads to an increase of the accretion rate, which, from its side, causes an increase of the rate of the nuclear burning.

The transition from quiescence to an active phase requires a sufficient increase in the accretion rate. According to the observational data, the mass-loss rate of the donor in Z And is $\sim 2 \times 10^{-7} M_{\odot}/\mathrm{yr}$. Since the amount of matter accumulated in the disk during the inter outburst period 1997–2000 should not exceed $\sim 5 \times 10^{-7} M_{\odot}$, the development of the outburst requires the accretion of the entire disk even in the framework of the combined model where the increase of the nuclear-burning rate is taking into account. As a rule, accretion-disk instabilities result in the infall of $\sim 10\%$ of the total mass of the disk, which is clearly not enough.

The required increase of the accretion rate can be provided in the framework of the mechanism suggested by us in [18], based on the results of two-dimensional gas-dynamical modeling and confirmed by three dimensional computations in our work [28] as well. According to that mechanism even a small increase of the velocity of the donor's wind is sufficient to change the accretion regime. At the time of the transition from disk acretion regime to wind one, the disk disrupts and the wind with increased velocity causes the infalling its material onto the surface of the accretor. The alalysis of the results of these computations has shown the following points.

1. Variation of 5 km/s of the observed donor's wind velocity of 25 km/s [3] is sufficient to change significantly the flow pattern as well as the accretion regime - from disk accretion to wind one. When the wind velocity amounts to 30 km/s, a conical shock forms. When it is equal to 20 km/s, an accretion disk appears in the system.

2. In the quiescence the accretion rate is $\sim (4.5 - 5) \times 10^{-8} M_{\odot}/\mathrm{yr}$ (for a mass-loss rate of the donor of $\sim 2 \times 10^{-7} M_{\odot}/\mathrm{yr}$ [3]) which corresponds

to the range of stable hydrogen burning for the adopted mass of the white dwarf in Z And.

3. If the wind velocity increases from 20 km/s to 30 km/s, the disk will disrupt and its material will fall onto the surface of the accretor.

4. The disruption of the disk is accompanied by a jump in the accretion rate (Fig. 3). A growth of the accretion rate by a factor of $\sim 2.0 - 2.2$ relative to its initial value provides exceeding the upper limit of the region of stable hydrogen burning. According to our computations the disk is fully disrupted in about 100 days and a mass of several units of $10^{-8} - 10^{-7} M_{\odot}$ accretes during that time. *Fig.3*

This amount of matter turns out to be sufficient to increase the pressure and the temperature providing an increase of the nuclear-burning rate. According to [8] the typical time scale for the response of the nuclear-burning shell after the accretion of a sufficient amount of matter is about one month, which is in good agreement with the observed time of the formation of a kink of the light curve. This time is 2.5 weeks after the onset of the outburst. The growth of the luminosity during the time interval before the increase of the burning rate is due to rise of the accretion rate. It means the time scale of that rise must be in agreement with that of the increase of the luminosity to the first kink of the light curve. In our computations the disk was fully disrupted in about 100 days. The inconsistency between the time scales can be compensated taking into account the nonuniform variation of the accretion rate. Figure 3 shows the accretion rate rises very rapidly and reaches its maximum in 10–20 days. If we suppose that the amount of matter accreted during that time is sufficient to initiate an enhanced burning rate, the further increase of the luminosity will be due to both the continuing accretion and the enhanced burning rate. According to [8] after the appearance of the first kink of the light curve associated with the enhancement of the burning rate, an expanding envelope – a pseudophotosphere and/or optically thick wind forms in the system.

It is commonly accepted that the increase of the visual light is due to the energy redistribution towards the longer wavelengths during the expansion of the envelope of the compact component [7, 32, 33]. However, an expansion of the envelope on its own is unable to explain the above features of the light curve. Moreover, the presence of the wind in the system should influence its brightness. If the wind of the white dwarf arises as the outburst progresses (after 2.5 weeks after the beginning of the outburst according to the data in[8]), it will seem that its influence will begin to manifest itself not at the very beginning of the outburst, but in its later stages.

Since the hot wind arises during the outburst, the curve of the optical light must be a sum of three components:

1) a luminosity variation causing an expansion of the pseudophotosphere (the increase of the flux of the nebula due to additional radiative ionization can be neglected, since it is proportional to the Lyman luminosity and does not change the shape of the curve);

2) a light increase due to the wind propagation in the nebula; at that the inflowing matter has the temperature of the hot wind, resulting in the formation of a high-temperature region in the nebula;

3) a luminosity increase due to the formation of shock structures appeared as a result of wind collision.

If the effects related to the wind are strong enough, they should be visible in the light curve. It is evident that the increase of the luminosity of the hot component and the expansion of its pseudophotosphere have the main contribution in the variation of the visual light. If at some time the component determined by the wind propagation in the nebula is added, followed by the formation of shocks providing further brightness increase, the resulting light curve will have two variations of its slope related to the hot wind.

The shape of the light curve will be more complex if the flux of the expanding photosphere has time variations. It is obviously that, at some time, the expansion of the photosphere will be replaced by a contraction. This time will correspond to a peak in the light curve. Its final shape depends on the time of the hot wind appearance (the second term), the time when the shocks form (the third term) and the position of the peak.

The increased accretion rate due to the disruption of the disk typically lasts for about 100 days. It means that the expansion of the envelope will stop after about 100 days, i.e. its flux (the first term) will begin to decrease, giving rise to a peak in the time interval $0^{\rm d}-100^{\rm d}$ in the light curve. The wind appears in this time interval too (after $\sim 20^{\rm d}$ after the onset of the outburst [8]). Starting with this time, the contribution of the high temperature region of the nebula to the luminosity of the system will be positive till the epoch of the wind disappearance. The velocity of the wind is about 50 km/s. Then, assuming the shock is located between the components of the system (at a distance of $1/3\,A - 2/3\,A$ from the accretor, where A is the component's separation), we can estimate the time that elapses before the contribution of the shock to become substantial. This time turns out to be 26– 52 days after the onset of the wind. The peak determined by the contribution of the shock will be attained after some time in addition.

To estimate the time scale of the shock's development we carried out a set of computations with parameters close to the conditions for the Z And outburst. The results show that after the change of the conditions at the accretor's surface an S-shaped shock structure and contact discontinuity form in the space between the components.

Figure 4 shows the development of events after the change of conditions at the accretor's surface. In the model presented the wind velocity at the accretor's surface is 50 km/s. The density distribution and the velocity vectors for the entire computational domain are shown for six times corresponding to 12, 42, 70, 103, 125, and 150 days after the start of the computations. Shocks are seen as concentrations of the density contours. The orbital motion of the accretor is counterclockwise. The dashed lines show the contours of the standard Roche potential. It is seen that the system of shocks forms fairly quickly – the shock occupies its final location on the X axis between the components already after about 70 days (Fig. 4c). The analysis of the results shows that the shock is established first between the components and in the regions above and below the line of their centers it forms definitively 20 – 30 days later (Fig. 4d). Further the parameters of the shock do not change substantially (Figs. 4d–4f). *Fig.4*

Summarizing the results of the numerical modeling it must be expected that the first component (the expansion of the pseudophotosphere) of the light curve will reach its maximum in the time interval from 0^{d} to 100^{d}. The contribution of the second component will begin to be significant in the same time interval and 70 days after that the third component will begin to make its contribution too. It will reach its maximum after 20 – 30 days in adition.

In our analysis of the light curve of the 2000 outburst of Z And we can assume that the first maximum, when the light rose by 1.9^m in ~ 60 days, is determined only by the expansion of the optically thick pseudophotosphere (the first term). It is known from observations [8] that the first kink of the light curve appeared close to September 15, 2000, and is related to the onset of the wind of the hot component. Assuming that the time of the wind appearance is close to September 15, 2000, it can be expected , according to our computations, that for a wind velocity of 50 km/s the shock will begin to form 70 days after the rise of the first kink, i.e. after the appearance of the wind. The analysis of the light curve shows that the second change of its slope realizes on November 13, 2000, i. e. after 60 days. The peak associated with the formation of the shock should be shifted at 20 – 30 days (according to the computations), while the observational data show that it forms after 25 days (December 6, 2000). Thus, the comparison of the results of the computations with the observations shows all main stages of the change of the light are in good agreement with the model.

To be sure that the presence of the wind (the second term) and the shock (the third term) really provide the observed light variations we must estimate their contributions.

The contribution of the hot wind to the light of the system can be estimated assuming that the location of the shock – the boundary of the areas of the two winds, is determined by the condition for equality of the ram pressures: $\rho_1 v_1^2 = \rho_2 v_2^2$. We can estimate the density of the hot wind assuming that the boundary is located in the middle of the components' separation (Fig. 4). Using the known parameters of the donor's wind (a mass-loss rate of $\sim 2 \times 10^{-7} M_\odot$/yr, a velocity of 30 km/s) and the velocity of the hot wind (50 km/s), we can estimate the mass-loss rate of the hot component. It turned out to be $\sim 1.2 \times 10^{-7} M_\odot$/yr.

Assuming that the hot wind is spherically symmetric we can calculate its UBV fluxes emitted by a spherical layer. The inner boundary of this layer is equal to $2.2 R_\odot$ and is close to the observed radius of the pseudophotosphere on November 22, 2000 and the outer one of $240.5 R_\odot$ is equal to the half of the component separation. The emission of the region beyond the outer edge can be neglected. It was supposed in our calculations that the gas consists of hydrogen and ionized helium (the wind region is hot), the helium abundance is 0.1, and the distance to the system is 1.12 kpc. The contribution of the wind in the UBV bands is shown in Tabl.1. It is seen that it is fairly large being on average $\sim 20\%$ on November 22, 2000. *Table 1*

In regard to the contribution of the shock, according to our computations we can present the following view. A calculated structure of the wind collision is presented in Fig. 5. The notation is similar to that in Fig. 4. The region in the vicinity of the shocks is shown in Fig.6 in more detail. *Fig.5*

Our analysis shows that the region between the shocks has a considerably higher temperature than the surrounding medium: on the X axis passing through the component centers, it is higher by a factor of 50 than in the *Fig.6* surrounding regions of the nebula and reaches 10^6 K. This is in agreement with the results of Nussbaumer and Walder [6] for their model of a symbiotic star with colliding winds. It was suggested in their work that just the high-temperature region between these shocks is the source of the X-ray emission observed from some symbiotic stars. Our estimates based on the method described in [13] show that for the assumed parameters of the winds and the computed area of the shock the X-ray luminosity is $10^{31} - 10^{32}$ erg. This result is in very good agreement with the observed X-ray luminosity during the 2000 outburst of Z And [8].

To estimate the contribution of the shocks in the total luminosity of the system we assumed that the light variations are proportional to the energy losses in the system. We made an approximation adopting that the radiative losses per unit time per unit volume are proportional to $\rho^2\Lambda(T)$, where $\Lambda(T)$ is the cooling function [34]. The total energy loss in the system was estimated as a sum over all cells in the computational domain. By means of computing the total energy loss for the time when the system of shocks was formed and comparing it with the energy loss in quiescence we can estimate the change of the light of the system. Our analysis shows that the quantity $\sum \rho^2\Lambda(T)$ can be appreciably higher after the formation of the system of shocks than in quiescence and the system of shocks can increase the light of the system by 1^m.

Summarizing our results we conclude that both the wind (the second term) and the shock (the third term) can significantly change the light of the system. Since the appearance of these phenomena in the framework of the model is at the same time as observed, we suggest that precisely they are responsible for the observed behavior of the light.

4 COMPARISON WITH OBSERVATIONS AND ANALYSIS OF THE CONTRIBUTION OF THE SHOCK TO THE TOTAL LIGHT OF THE SYSTEM

In the previous section we showed that the proposed scenario of the outburst based on our modeling is in good agreement with the observed temporal behavior of the light. If this model is correct, the presence of the shock will also result in other observable effects, for example, such as existence of shock ionization. Let us consider some rezults of the observations of the Z And outburst.

According to the observational data [8, 32], the last stage of the rise of the light started on November 13, 2000 (JD 2451862) and lasted for about 25 days. In the proposed scenario this stage is provided by formation of a system of shocks resulting from the collision of the winds. To estimate the influence of these shocks on the light of the system we used the results from the work of Tomov et al. [32], where the basic parameters of the system's components (the cool component, the hot component, and the nebula) and their continuum fluxes were estimated from observational data.

The continuum fluxes of the components of Z And in units of 10^{-12} erg$\cdot$cm^{-2}s^{-1}Å^{-1} for November 22 and December 6, 2000 [32] are listed in Table 2. These data show that the emission of both the nebula and the hot component increased during this time interval. We used the difference between the total (model) and the observed fluxes as a percentage of the observed flux as a criterion for the agreement between the model continuum and the observed one. On the other hand, the UV continuum fluxes at wavelengths 1059 and 1103 Å where only the hot component emits, taken from the work of Sokoloski et al. [8], show that its emission increased during the period November 16 – November 27, 2000, and was constant after that, till December 15, 2000. The result of the continuum analysis is in qualitative agreement with the UV data, as far as the time interval November 22 – December 6 covers the interval November 22 – 27 when the emission of the hot component was rising. However, since this emission was not changing between November 27 and December 15, we propose a second variant of the continuum analysis for December 6 too in Table 2, with a smaller growth of the radius of the hot component. When we calculate the emission due to shock ionization we shall consider this second variant too, since it is in better agreement with the observed behavior of the hot component in the UV, although the total and the observed fluxes in the infrared are in better agreement in the first variant. *Table 2*

According to the proposed model three processes contribute to the light curve: the rise of luminosity causing an expansion of the envelope, the rise and development of the high temperature region in the nebula formed by the white dwarf's hot wind, and the shock structure formed by the collision of the winds.

The observed $UBVRIJHKLM$ fluxes at different times are shown in

Fig.7. These times are as follows: quiescence, the onset of the last stage of the growth of the light (November 13, 2000), some time of the rise to the second maximum (November 22, 2000) and some time close to the light maximum (December 6, 2000). These data show that the flux at shorter wavelengths *Fig.7* grows more when the optical light goes toward its second maximum. Most probably it is due to the appearance of the hot wind and the formation of the shocks.

The most correct approach to determine the contribution of the shock is to estimate the shock ionization. Let us consider the ratio of the number of ionizing photons and the number of recombinations in the nebula μ in the quiescence and on November 22 and December 6, 2000. This ratio is estimated as

$$\mu = \frac{L}{n_e n_+ \alpha V} \ ,$$

where L is the Lyman photon luminosity of the hot component, n_e and n_+ are the number densities of the electrons and ions respectively, α is the total (to all levels) recombination coefficient, and V is the volume of the nebula. The Lyman luminosity is

$$L = 4\pi R^2 H_{\lambda<912} = 8\pi^2 \frac{R^2}{c^2} \left(\frac{kT}{h}\right)^3 G(T) \ ,$$

where R and T are the radius and effective temperature, $G(T)$ is a function related to the number of the ionizing photons (given in numerical form in the book of Pottasch [35]), and the remaining quantities have their commonly accepted meaning. The number of recombinations is

$$n_e n_+ \alpha V = [1 + a(\mathrm{He})]\, \alpha n^2 V \ ,$$

where a(He) is the number abundance of helium relative to hydrogen. If we obtain from observations the radius and the effective temperature of the hot component and the emission measure of the nebula in addition, we will calculate the ratio μ.

In the state of ionization equilibrium when only radiative ionization is realized in the nebula μ $\geq$1. The equality is satisfied when all photons are absorbed in the nebula. When μ¡1 the number of recombinations is greater, which means that shock ionization is realized in the nebula along with radiative one. The ratio of the continuum fluxes due to shock and radiative ionization is $(1-\mu)/\mu$ when all photons are absorbed in the nebula.

In some cases of the distribution of the circumstellar gas some fraction of the photons can leave the nebula. Then $(1-\mu)/\mu$ is a lower limit of the ratio of the parts of the continua corresponding to shock and radiative ionization.

The ratio μ was calculated with use of the parameters of the system's components determined for different times during the outburst in the work of Tomov et al. [32]. These authors found that the dominant ionization state of helium in the nebula in quiescence is He^{++} and during the outburst – He^{+}. It was assumed that the nebular continuum in quiescence is emitted by hydrogen and ionized helium and during the outburst – by hydrogen and neutral helium. These assumptions were taken into account when computing μ. For this purpose the value of $a(\mathrm{He})$ was doubled for quiescence. The helium abundance was taken to be 0.1, in accordance with the results of Nussbaumer and Vogel [5]. It was assumed that the average number density in the Z And nebula is $10^8 - 10^{10}$ cm^{-3} [3, 36–38]. The recombination coefficients were taken from [39] for Menzel case B.

The computational results and their rms errors are presented in Table 3. The errors were derived from the uncertainties of the parameters of the system given in [32]. We did not present the error for the quiescence, since in this case the Lyman luminosity was calculated using the average temperature from the results of other authors, based on UV data. We present both variants for December 6, 2000. *Table 3*

The data in Table 3 show that $\mu > 1$ in quiescence (September 15, 1999). It is known that the Z And nebula is partially ionized in quiescence [3, 37, 38, 40] and our result (within the errors) indicates that some fraction of the photons leave the ionized region. The ratio μ is equal to unity for November 22, 2000 (less than in quiescence) and less than unity for December 6, 2000. Thus it decreases with time, which means that the role of the shock ionization increases.

The second variant for the time of the light maximum proposes $\mu = 0.76$. This means there is no doubt that the shock ionization takes place and its contribution to the emission of the nebula is not less than 0.24 (since some fraction of the photons can leave the nebula). This contribution can be as high as 0.44 when we take into account the observational uncertainties. The UBV fluxes determined by the shock ionization in the case of $(1-\mu) = 0.24$ are presented in Table 4. The contribution of the wind is presented also in this table. This contribution is the same for the two epochs since the parameters of the wind are considered to be constant and, according to the model (Fig. 4), the boundary between the winds does not change after some *Table 4* time. Subtracting the contribution of the hot wind and the shock from the total emission of the nebula, we find that the flux of its cool part changes because of the increase of the radiative ionization during the period November 22 – 27, 2000 resulting from the growth of the hot component's luminosity. This change, however, is insignificant.

Thus, our analysis of the observational data shows that the light variations at the last stage of the outburst's development are well explained by means of the proposed scenario and consequently can be interpreted in the framework of the model of the colliding winds.

5 CONCLUSION

We have used the results of gas-dynamical modeling of flow structures to study the development of the outburst in the symbiotic system Z And.

The analysis of the Z And outburst in 2000 shows that the accretion processes are not able to provide the observed energetics of that event. As a possible mechanism of the outburst's development we considered a combined case when the increase of the accretion rate as a result of the disruption of the disk leads to variation of the burning rate. This model was proposed in [18, 29–31] where it was assumed that the variations of the velocity regime of the donor's wind result in disruption of the accretion disk and the infall of a considerable amount of its matter ($10^{-8} - 10^{-7} M_{\odot}$ according to [28]) onto the surface of the white dwarf. This is enough to initiate an increase of the rate of the nuclear burning and, consequently, the subsequent increase of the luminosity (the development of the outburst) will be determined by both the ongoing accretion and the increased nuclear-burning rate.

According to Sokoloski et al. [8] who analyze a similar combined outburst model, an expanding envelope (pseudophotosphere) and/or optically thick wind form in the system after the first kink of the light curve, which is associated with an enhancement of the nuclear burning. The presence of the wind in the Z And system during its 2000 outburst is confirmed by numerous observations in the UV, optical and radio regions. In this case the curve of the optical light will be formed by (1) a luminosity variation leading to an expansion of the pseudophotosphere, (2) a light increase due to the wind propagation in the nebula, (3) a luminosity increase due to the formation of shock structures appeared as a result of wind collision. As it is seen from the results of the computation of the gas-dynamical structure, the effects associated with the wind are fairly strong and just they determine the complex stage-by-stage nature of the rise of the light during the period when the outburst progresses.

The proposed scenario for the development of the outburst provides an explanation of the behavior of the light, which is consistent with the available observational data – it is in accordance with the observed temporal characteristics, amplitudes and scale of the shock ionization.

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Table 1: Emission of the hot wind

Photometric waveband	Flux, 10^{-12} erg$\cdot$cm^{-2}s^{-1}Å^{-1}	Fraction of the nebula emission on November 22.11.2000
U	0.4646	23%
B	0.1346	19%
V	0.1180	19%

Table 2: Continuum fluxes of the Z And components (in 10^{-12} erg·cm^{-2}s^{-1}Å^{-1}) [32]

Emission source .*	U	B	V	R	I	J	H	K	L	M
November 22 2000 ($R_{\rm hot} = 2.22 R_\odot$, $n^2V = 17.4 \times 10^{59}$ cm^{-3})										
Cool component	0.020	0.160	0.376	0.710	1.755	1.343	0.856	0.439	0.113	0.034
Hot component	5.537	2.934	1.336	0.730	0.340	0.063	0.022	0.007	–	–
Nebula	1.983	0.717	0.631	0.547	0.432	0.147	0.081	0.051	0.020	–
Total flux	7.540	3.811	2.343	1.987	2.527	1.553	0.959	0.497	0.133	0.034
Observed flux	7.205	3.848	2.492	–	–	1.591	0.927	0.461	0.117	0.024
Observational error	0.054	0.036	0.022	–	–	0.002	0.001	0.001	0.001	0.001
Deviation D	5%	-1%	-6%	–	–	-2%	3%	8%	14%	42%
December 6 2000 – variant 1 ($R_{\rm hot} = 2.36 R_\odot$, $n^2V = 20.9 \times 10^{59}$ cm^{-3})										
Cool component	0.020	0.160	0.376	0.710	1.755	1.343	0.856	0.439	0.113	0.034
Hot component	6.257	3.315	1.510	0.826	0.384	0.071	0.024	0.008	–	–
Nebula	2.382	0.861	0.758	0.657	0.519	0.176	0.098	0.061	0.024	–
Total flux	8.659	4.336	2.644	2.192	2.658	1.590	0.978	0.508	0.137	0.034
Observed flux	8.662	4.257	2.682	–	–	1.635	0.944	0.478	0.120	0.024
Observational error	0.064	0.039	0.023	–	–	0.001	0.001	0.001	0.001	0.001
Deviation D	0%	2%	-1%	–	–	-4%	4%	6%	14%	42%
December 6 2000 – variant 2 ($R_{\rm hot} = 2.28 R_\odot$, $n^2V = 24.0 \times 10^{59}$ cm^{-3})										
Cool component	0.020	0.160	0.376	0.710	1.755	1.343	0.856	0.439	0.113	0.034
Hot component	5.841	3.094	1.410	0.770	0.358	0.066	0.023	0.007	–	–
Nebula	2.737	0.989	0.871	0.754	0.600	0.202	0.114	0.074	0.030	–
Total flux	8.598	4.243	2.657	2.234	2.713	1.611	0.993	0.520	0.143	0.034
Observed flux	8.662	4.257	2.682	–	–	1.635	0.944	0.478	0.120	0.024
Observational error	0.064	0.039	0.023	–	–	0.001	0.001	0.001	0.001	0.001
Deviation D	-1%	0%	-1%	–	–	-1%	5%	9%	19%	42%

* Total flux = hot component + cool component + nebula,
deviation from observations D = (total flux – observed flux)/observed flux.

Table 3: Ratio of the numbers of ionizing photons and of recombinations at various times.

Date (state of the system)	μ
15.09.1999 (quiescence)	1.12
22.11.2000 (outburst, rise to the second maximum)	$1.00^{+0.25}_{-0.21}$
06.12.2000 (outburst, close to the maximum) – variant 1	$0.94^{+0.24}_{-0.20}$
06.12.2000 (outburst, close to the maximum) – variant 2	$0.76^{+0.24}_{-0.20}$

Table 4: Fluxes from various regions of the nebula (in units of 10^{-12} erg$\cdot$cm^{-2}s^{-1}Å^{-1})

Source	U	B	V
22.11.2000			
Entire nebula	1.983	0.717	0.631
Hot wind (second term)	0.465	0.135	0.118
Shock (third term)	0	0	0
Cool region of the nebula	1.518	0.582	0.513
06.12.2000 – variant 2			
Entire nebula	2.737	0.989	0.871
Hot wind (second term)	0.465	0.135	0.118
Shock (third term)	0.657	0.237	0.209
Cool region of the nebula	1.615	0.617	0.544

FIGURE CAPTIONS

Fig. 1. The UBV light curves of Z And during the 2000 outburst. Data of Skopal et al. [19, 20] (points) and our own data (crosses) are shown. The first and second light maxima are marked by dashed lines and the times for which the ratios of ionizing photons and recombinations μ were calculated – by arrows. The inserts show the behavior of the light near its maximum on a larger scale.

Fig. 2. The light curve of Z And during the 2000 outburst, from Sokoloski et al. [8].

Fig. 3. Variation of the accretion rate for the solution with an increase of the wind velocity from 20 to 30 km/s. The vertical dashed line marks the time when the wind velocity changes.

Fig. 4. Contours of equal density and velocity vectors for six moments during the outburst's development: (a) 12, (b) 42, (c) 70, (d) 103, (e) 125, and (f) 150 days after the start of the computations. The hollow circle denotes the donor (the radius corresponds to the donor radius).

Fig. 5. Contours of equal density and velocity vectors for the two-dimensional computations. The hollow circle denotes the donor (the radius corresponds to the donor radius). The distances are in solar radii.

Fig. 6. Contours of equal density and velocity vectors in the region of the shocks.

Fig. 7. The observed fluxes in the $UBVRIJHKLM$ wavebands.

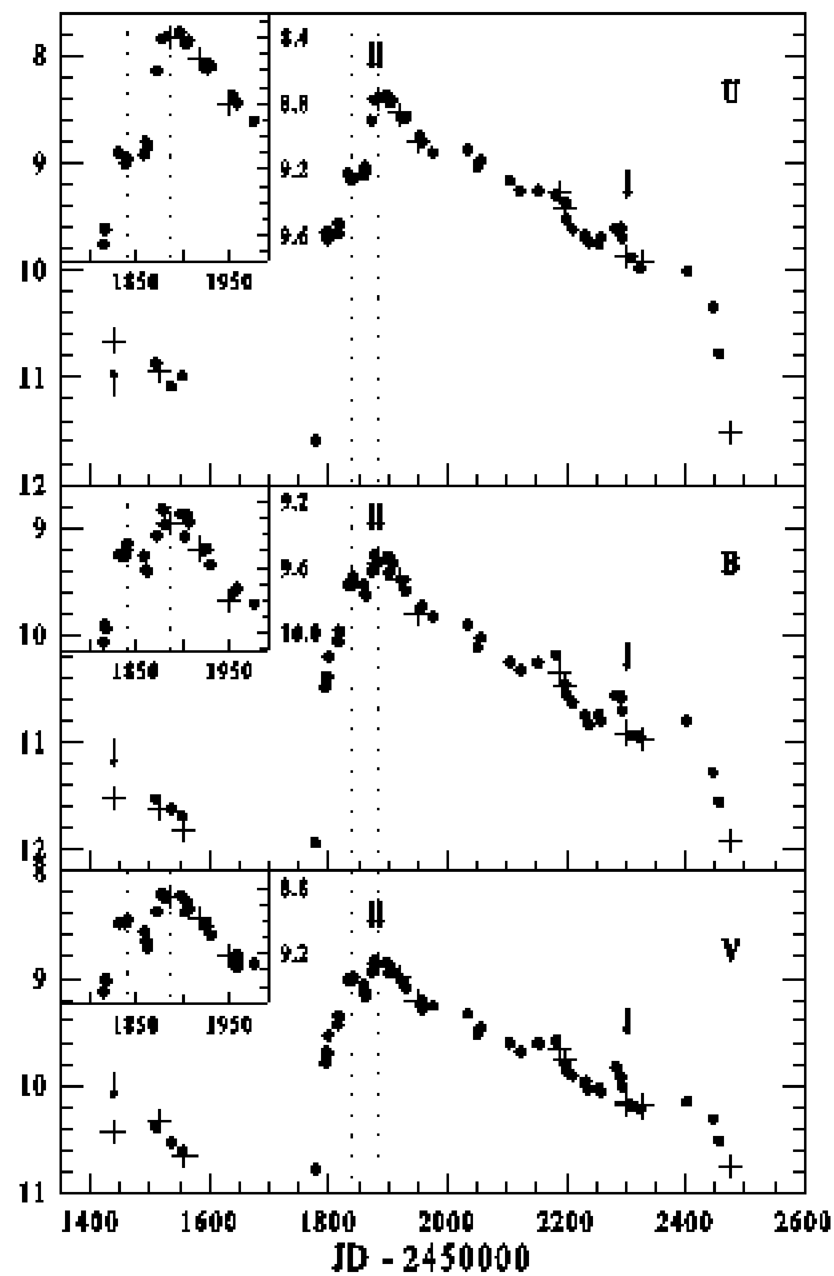
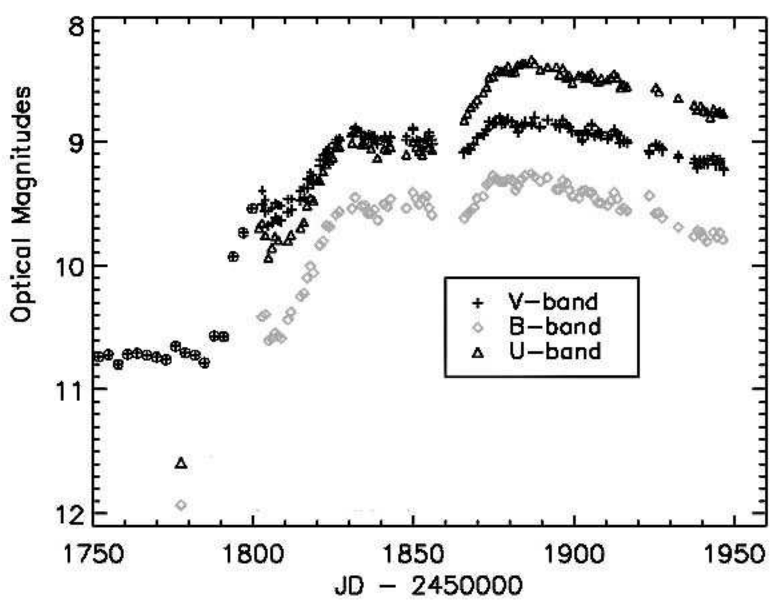
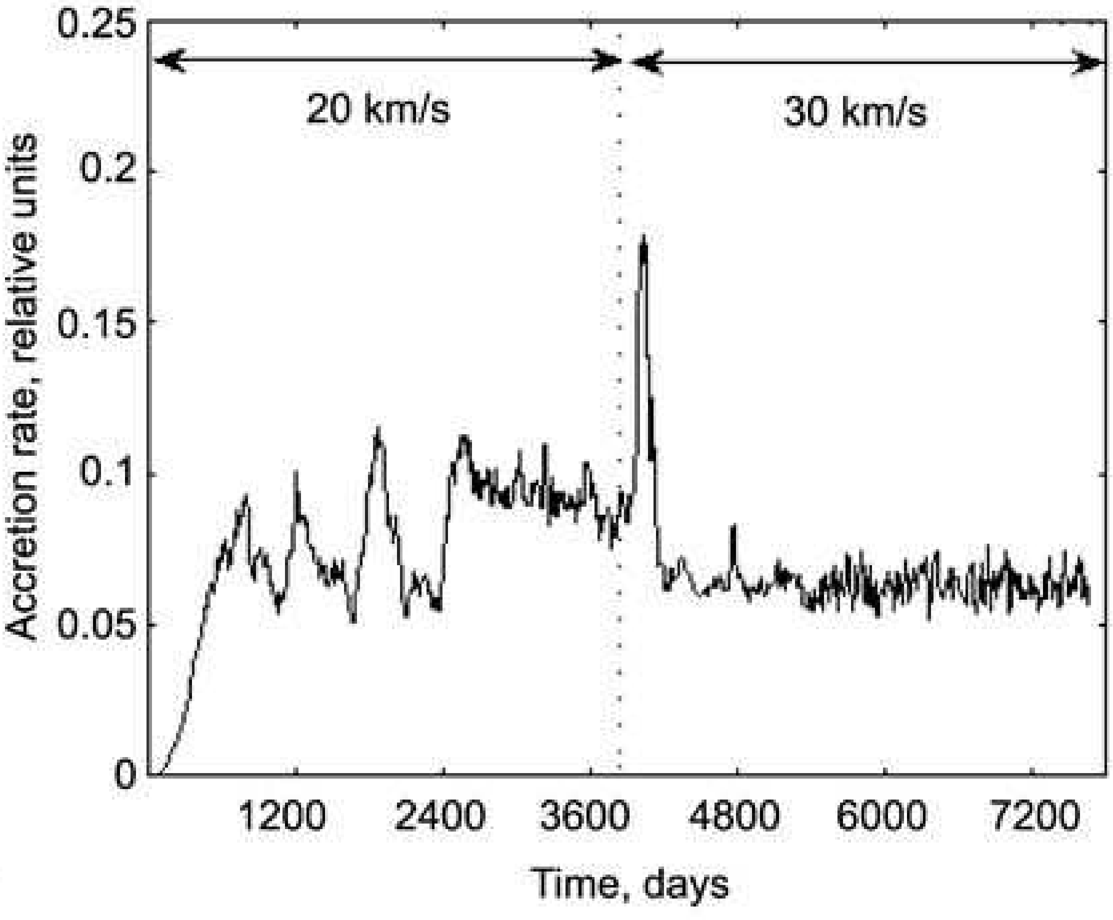

U
B
V
8
9
10
11
12
9
10
11
12
8
9
10
11
8.4
8.8
9.2
9.6
9.2
9.6
10.0
8.8
9.2
1850
1950
1850
1950
1850
1950
1400
1600
1800
2000
2200
2400
2600
JD - 2450000

Fig. 1.



Optical Magnitudes
JD − 2450000
V−band
B−band
U−band
8
9
10
11
12
1750
1800
1850
1900
1950

Fig. 2.



20 km/s
30 km/s
Accretion rate, relative units
0.25
0.2
0.15
0.1
0.05
0
1200
2400
3600
4800
6000
7200
Time, days

Fig. 3.

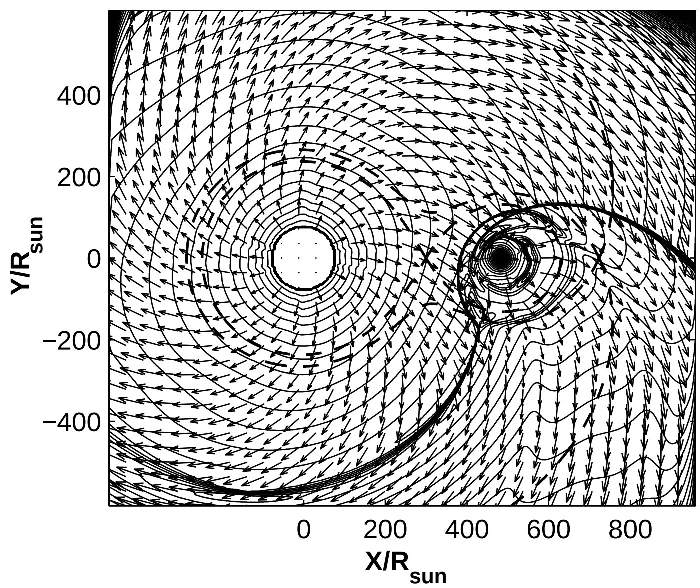


Fig. 4a.

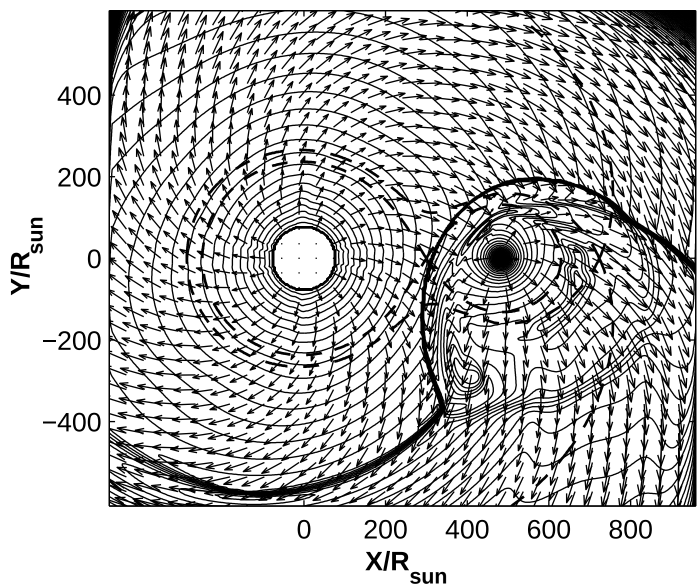


Fig. 4b.

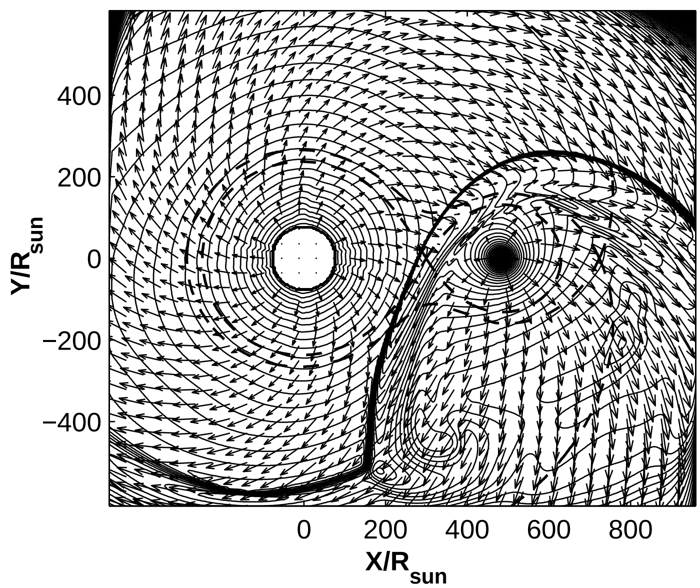


Fig. 4c.

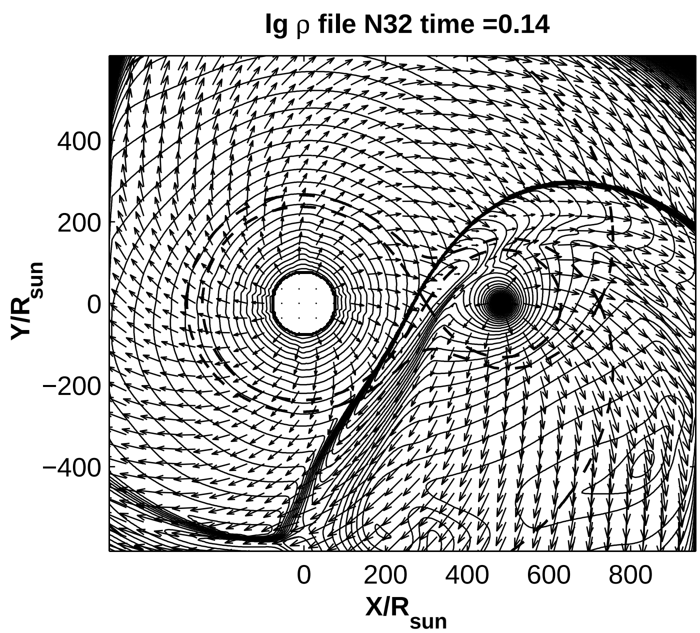

lg ρ file N32 time =0.14
400
200
0
−200
−400
Y/R_sun
0
200
400
600
800
X/R_sun

Fig. 4d.

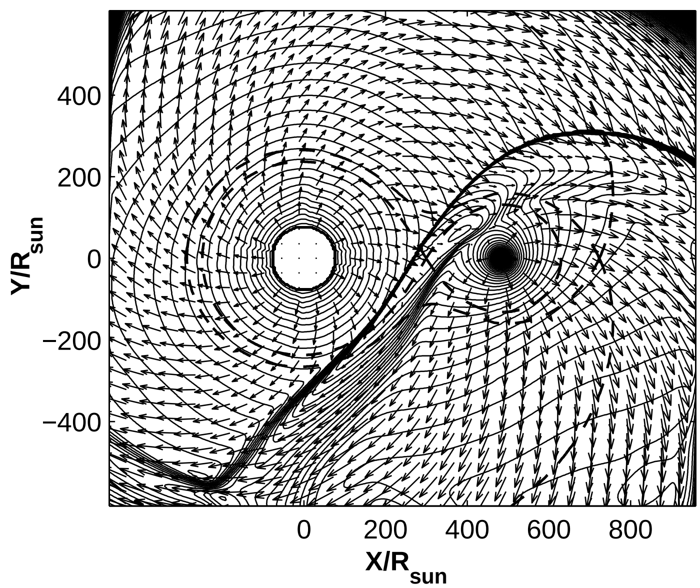


Fig. 4e.

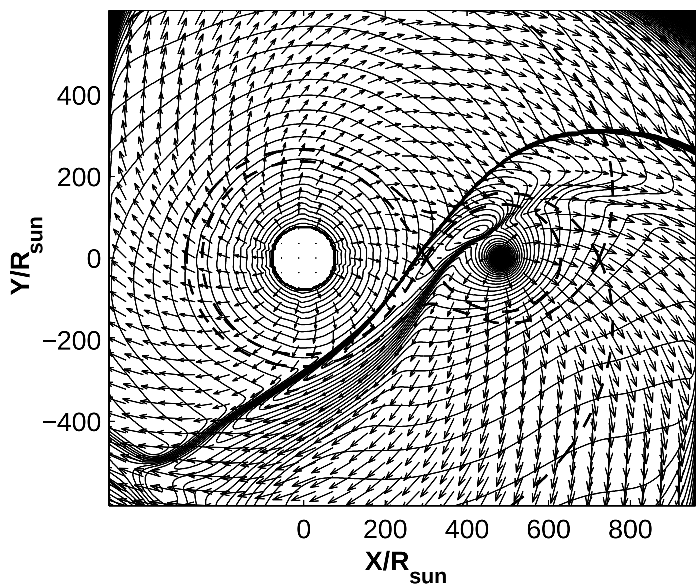


Fig. 4f.

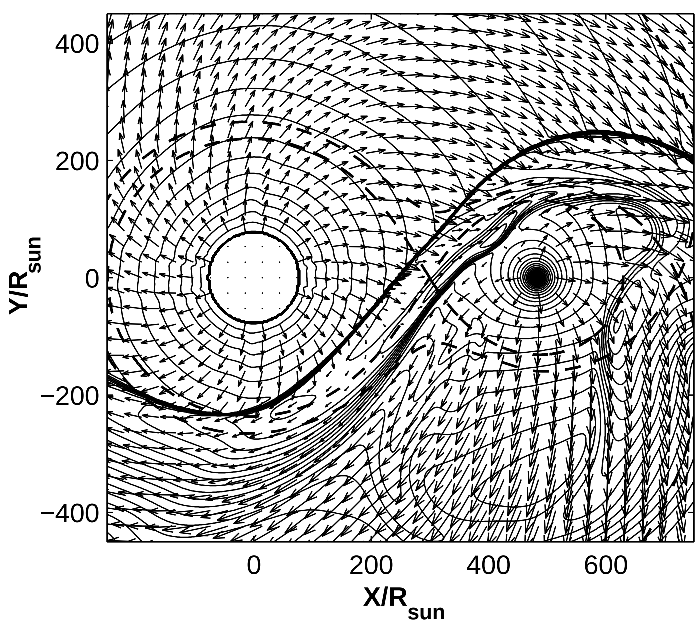


Fig. 5.

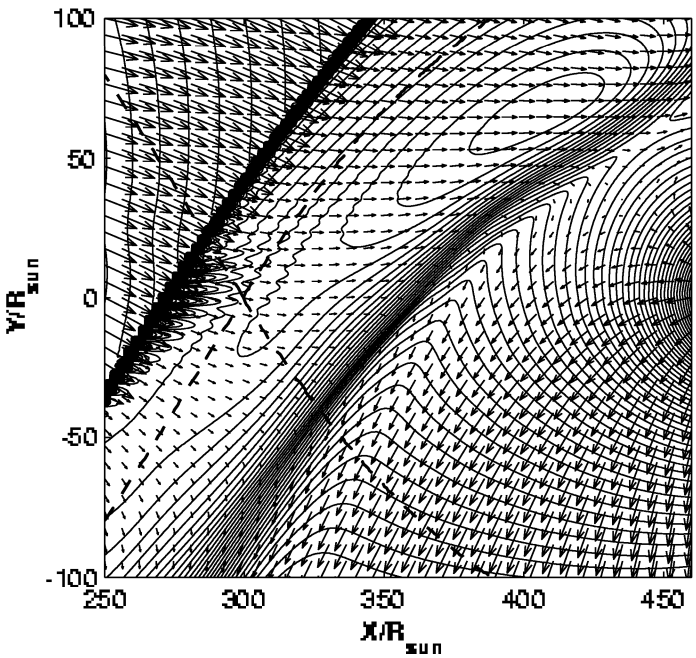


Fig. 6.

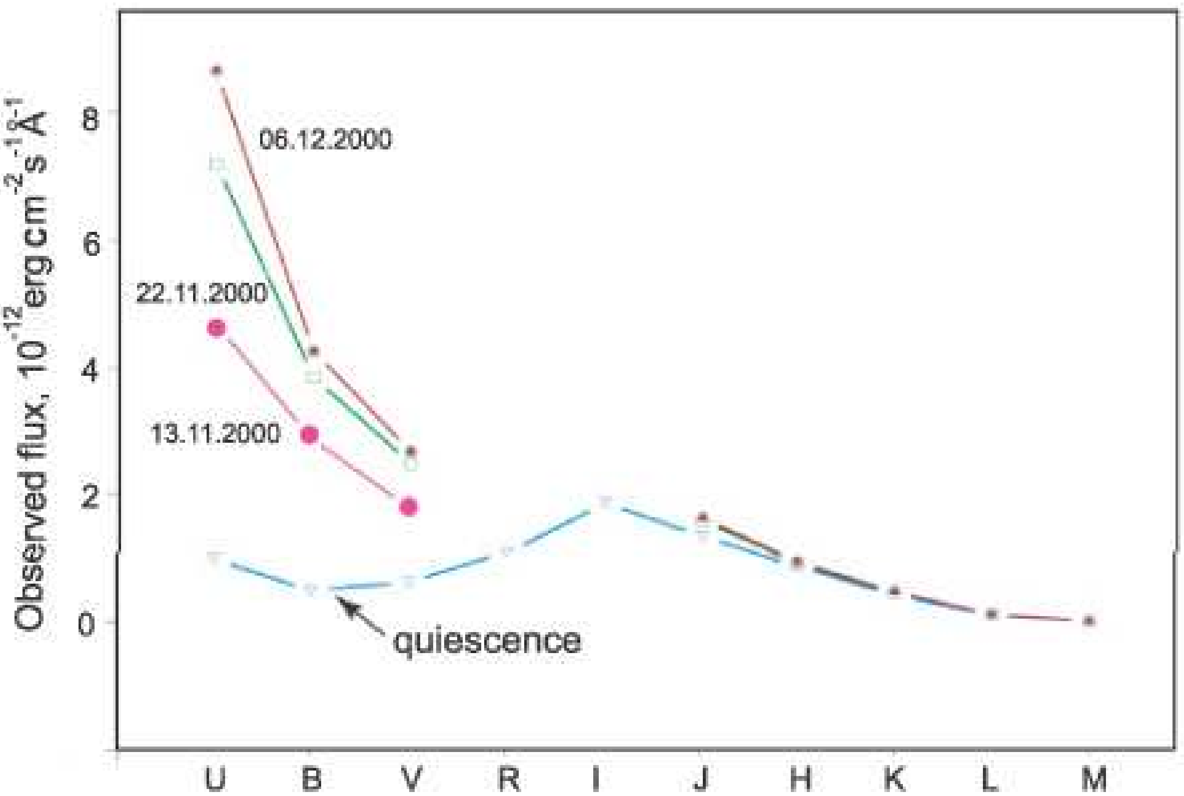

Observed flux, 10^{-12} erg cm^{-2} s^{-1} Å^{-1}
0
2
4
6
8
06.12.2000
22.11.2000
13.11.2000
quiescence
U
B
V
R
I
J
H
K
L
M

Fig. 7.